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ADDITIONAL EFFORT IN MODELING OF THE
NON-AUDITORY EFFECTS OF BLAST

FINAL REPORT

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The work summarized in this report deals with four research areas. The first is the collection, organization, and analysis of animal pathology data which forms the basis for our current understanding of blast related hazard. The second is the refinement and validation of our predictive models of blast injury for the free-field that is the basis for our theoretical understanding of the phenomena and our means to set safety standards. The third is the modeling of combined battlefield trauma which is required to establish combat medicine needs. The fourth is the understanding of blast in complex environments where hazards are increased. Sections 2 through 5 summarize the findings in these areas and guide the reader to other technical documents where the work is described in detail.

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1. INTRODUCTION

Background

The work summarized in this report deals with four research areas. The first is the collection, organization, and analysis of animal pathology data which forms the basis for our current understanding of blast related hazard. The second is the refinement and validation of our predictive models of blast injury for the free-field that is the basis for our theoretical understanding of the phenomena and our means to set safety standards. The third is the modeling of combined battlefield trauma which is required to establish combat medicine needs. The fourth is the understanding of blast in complex environments where hazards are increased. Sections 2 through 5 summarize the findings in these areas and guide the reader to other technical documents where the work is described in detail.

To understand the importance of the findings of the current modeling project, it is helpful to review the state of knowledge of blast overpressure injury a decade ago when the modeling effort was initiated and how the needs of Army have evolved.

Tools Available for Assessing Blast Injury. Two methods existed for assessing blast overpressure injury: one, Mil. Std. 1474B, for use in occupational situations, and the other, the Bowen curves, for use in combat conditions.

Mil. Std. 1474-B is a standard developed for auditory effects expressed in terms of peak pressure level and duration. It contains the so-called "Z-line," above which no soldier should be exposed because of possible nonauditory injury that no amount of hearing protection could prevent. The nature of that injury is unspecified and the curve was not based on any observational data, although it might have reflected the intuition of the committee. The other curves in the Mil. Std. were based primarily on small calibre weapons and, at the time of its creation, the Z-line was well removed from any operational weapon system.

The second method available was Bowen's curves, again, relations in terms of peak pressure and duration, albeit a duration with a slightly different definition. These curves give the blast overpressure conditions at which threshold lung injury occurs and the conditions for which 50% of the animal subjects died (LD50). The data was collected primarily for the Defense Nuclear Agency (DNA) in order to describe nuclear blast effects. Most of the tests were made in the free field with large explosives, producing a family of blast curves that are very regular and readily described by two parameters: the peak pressure and the positive overpressure duration. The blast was always unidirectional and of such long duration that the subject was completely immersed in the overpressure. Because there are only two degrees of freedom to the blast wave, it was possible to study the effect extensively, even using a variety of species.

Situations of Interest to US Army. The blast overpressure exposures of concern to the US Army, however, do not match either of these categories.

On one hand, for occupational exposures during training, large calibre field artillery produce pressure traces in the crew areas that exceed the Z-line. These signals are similar to free field explosions at intermediate distances, that is, they have longer durations than small calibre fire and yet shorter durations than the conditions studied for DNA.

On the other hand, there is a growing need for injury assessment from blast in armored fighting vehicles. The blast signals in these cases are characterized by relatively low peaks but long, reverberant durations. The signals follow no obvious pattern and can vary considerably from one location to another in the vehicle, earning them the name "complex."

The results of applying the conventional tools to these problems was disconcerting. The large calibre weapons clearly exceed the allowable limits, although there was a general feeling that no acute injury was occurring. Still, for occupational health, chronic injury must be considered. When the Bowen methodology was applied to the behind armor data, the results were completely arbitrary. If the methodology were followed rigorously, using the peak pressure and the time to the first zero overpressure, the curves would consistently under predict injury. If the "sensible" duration were selected, that is, the time at which the overpressure sensibly vanished, the injury predictions were over predicted. A variety of ad hoc rules were suggested to apply the Bowen curves in a way that gave "reasonable" answers. The results were not satisfying.

US Army Responses. To address these issues, the Army took several direct actions. Man-rating studies were initiated for the various weapon systems that exceeded the Z-line. In very careful tests, hearing decrements were measured after exposure to various numbers of firings and an upper limit on exposures per day was established. Needless to say, these studies are very long and costly. Laryngoscopic examinations were used to detect precursory nonauditory injury.

Animal studies were undertaken at the Kirtland Blast Overpressure Site to extend the understanding of combat level exposures. Data taken under conditions more relevant to conventional weapon exposure produced threshold lung injury curves in conflict with the predictions of Bowen. There are situations, for example, in which one correlation predicts no injury, while the other predicts severe injury.

The same studies revealed another effect, that wearing a Kevlar ballistic garment significantly increases the occurrence and severity of lung injury. Naturally, none of the existing methodologies accounts for, or even acknowledges, such an effect.

Animal testing was used in the first defeated vehicle tests, but, for a variety of reasons, was discontinued before it was possible to develop any substantial understanding of how injury estimates should be made. Subsequently, tests were

conducted at the Kirtland site using various sized and shaped enclosures. Two trends became immediately clear. First, it was possible to produce extreme injury in an enclosure for a charge and distance combination that in the free field would produce no injury at all. Second, it was very difficult to design tests that produced a desired level of injury, for example, threshold. One tended to get a lot or nothing. When explosives more representative of anti-vehicle weapons were used, the results were even less predictable.

Statement of Problem. It became clear that there was no fundamental understanding of the injury process and, therefore, no way to reliably extrapolate previous animal tests. The reliance on the empirical experience that had been gained for long-duration, free field blast waves and that was encapsulated in the two-parameter Bowen correlations of injury not only could not be applied, but was leading the testing effort down blind alleys.

Field testing had never been conducted with the goal of systematically developing such an understanding. Each test series had been motivated by some specific application. Consequently, grading of injury and description of the blast overpressure varied for test to test. In fact, the data had never been systematically compiled and analyzed.

Furthermore, animal testing is becoming less desirable. Complex waves present too many possibilities to approach in a brute force way. With limited time and resources, it is necessary to have a more scientific approach to the task of estimating blast overpressure injury.

Previous Modeling Effort

JAYCOR has been involved in the assessment of blast injury for the US Army Medical Research and Development Command for over 10 years. We began by assisting WRAIR in the measurement and interpretation of field data for the first howitzer tests. At each step, it became clear that field or laboratory data in itself could not answer the questions at hand. Consequently, we have developed models for the blast field around weapons, the propagation of blast to and around bodies, and the dynamic response of the biological system all the way down to the tissue level. The discussion below summarizes that effort, its goals, accomplishments, and unresolved issues. The most critical of those unresolved issues form the basis for the effort described in the remaining sections.

Goals of the Previous Projects. The modeling effort has two principal goals. The first is to develop a true, mechanistically correct understanding of the processes responsible for blast overpressure injury. The basic tenet of the technical approach is that injury should correlate with stresses acting on the tissue no matter what the nature of the external stimulant. This part of the project can be characterized as a basic research endeavor.

The second goal is to provide a best-estimate capability to predict injury. This objective reflects the reality that understanding will always be growing and requirements evolving, but there is an immediate need for a well-founded estimate.

Scope of the Work. The scope of these projects was very broad. All nonauditory organs affected (tympanic membrane, upper respiratory tract, lung, and the gastrointestinal tract) were to be considered. Separate research efforts were established for each organ, although the lung received the majority of the effort.

Another aspect of the project was to interact with and support research programs in-house at WRAIR and field testing at the Kirtland site.

Finally, priorities were set quarterly at the project review meetings to guarantee that the effort was addressing the Army's immediate needs, while maintaining a vigorous research program. For example, URT modeling, which was not given much importance at the beginning of the effort, was pursued intensively at the time that WRAIR needed to modify the damage risk criteria for occupational exposure. Complex wave analysis became the principal theme of the later stages of the project as the inadequacy of the Bowen model and the urgency of the behind armor effort became apparent.

Previous Accomplishments

We have been able to express equal-injury conditions in terms of equal-tissue response for the URT, TM, and Lung and we have provided simple, practical tools for estimating gross injury that replace both the Z-line of the Mil. Std. and the Bowen curves. A brief discussion highlighting some of these accomplishments follows.

Ballistic Garment Effect. Definitive laboratory tests have been conducted that show that the ballistic garment increases the load delivered to the body. As a by-product of our investigation into parenchymal dynamics, we found a mechanical equivalent to the jacket effect that allows a controlled study of the phenomena. With this insight and data, a computational model was developed that could be used to guide the design of a better garment and could form the basis for a model for the prediction of enhanced injury.

Tympanic Membrane. A finite element structural model of the tympanic membrane was developed. When the model was subjected to a pressure loading it responded dynamically, producing regions of stress concentration near the manubrium and in radial bands outward toward the tympanic ring. These stress concentration points correspond to locations of observed membrane rupture in animals.

Based on the full structural model, a simplified response model was constructed so that dynamic analyses of blast loading could be readily made. Previously measured properties of the membrane elasticity and breaking strength of the collagen fibers were used to establish a range of tissue stresses likely to cause rupture.

The model was compared to the extensive data of James, et al., in which load at the membrane and damage to cadaver ear drums were measured. The occurrence and severity of tympanic membrane rupture were found to correspond to the tissue stress calculated.

Upper Respiratory Tract. A simplified structural model was developed to transform the pressure loading forces on the external surface of the neck into tissue stress on the inner tracheal wall. Measurements of blood vessel critical stresses were used to establish failure limits.

Working together with Ken Dodd of WRAIR, data on upper respiratory tract injury from Kirtland field tests were compiled and graded. Data from single shot exposures confirmed the predictions of the structural model.

To explain the blast levels required to produce injury during multiple shot exposures, a model of material failure patterned after fatigue failure was conceived. Using values characteristic of other structural materials, reduced strength estimates were made for repeated exposure. When compared to the entire data base, injury from 1, 5, 20, and 100 shot exposures could all be predicted from the same material properties model.

Further investigation of the model's predictions reveals that, for simple free field explosions, the threshold for URT injury corresponds very closely to the Z-line of Mil. Std. 1474B.

It is now possible to replace the nonauditory criteria of the Mil. Std. with a unambiguous and tested methodology that not only applies to free field exposures, but can be used in complex wave environments to estimate occupational hazard.

Lung. The lung received the largest research effort and, consequently, had the greatest number of findings and results. A brief synopsis of those results follows.

Although the functional nature of the lung is well understood, the mechanical properties of the parenchyma, especially under dynamic conditions, was not well understood. In a series of in vitro tests with lung tissue, all of the viscoelastic properties were determined. The most dramatic of these is the combination of relatively high mass density and high compressibility which leads to very slow propagation of pressure waves. This slow response of the lung to mechanical motion is the primary reason for injury at the pleural surface. Other properties measured, included the tissue stress-strain relations, which play a role in determining the mechanical failure limits of the tissue.

Working together with Ken Dodd of WRAIR, a series of field studies was conceived, executed, and analyzed that revealed the dynamic character of the thorax. Surprisingly, it was found that the thorax response is dominated by the inertia of the chest wall, rather than any elastic forces from the rib cage. This result is in sharp

contrast to dynamics under blunt trauma. This finding allowed a series of computational models of the thorax and lung to be constructed.

Using the knowledge of the thorax mechanics and the finding that foam has the same mechanical properties as the parenchyma, a mechanical surrogate of the chest wall-lung tissue was constructed. With this device it is possible to study thorax and pleural dynamics with complete control.

One finding of the surrogate tests was that under sufficiently large chest wall velocities, the parenchyma develops a pressure concentration similar to a shock wave in a gas. Associated with this "parenchymal shock" is a loss of mechanical energy, a dissipation that, in an living organ, might correspond to damage.

Again, field tests were conceived and during one of the last test series made at Kirtland, direct evidence, from pressure probes inserted into the lung, was found for the occurrence of a parenchymal shock near the pleural surface.

The parenchymal shock was also simulated in our lung tissue computational model and a simple relation between parenchymal pressure and chest wall velocity was developed. That simple relation made it possible to develop a single-degree of freedom model of the thorax that predicts the pleural pressure.

Further investigation revealed that the total work done against this irreversible force correlates well with pleural damage seen in field tests. In order to test this finding, a considerable amount of effort was exerted into collecting and compiling the existing lung injury data. That collection, while far from acceptable in terms of its qualification, nonetheless shows the validity of the so-called "work correlate of injury."

With the work correlate, it is possible to bring together all of the previous injury data. Differences between the WRAIR and Bowen results can be understood. Multiple-shot and multiple-exposure data follow the same pattern. Even when the correlate is applied to explosions within enclosures the correlation is quite satisfactory.

Finally, direct investigation of the injury mechanism with microphotography and scanning electron microscopy has been performed. Blast injured lung tissue shows mechanical damage in the regions where gross hemorrhage is observed. It would be desirable to complete the understanding of lung injury be relating the mechanical correlate directly to the material properties of the parenchyma.

Computational Models. The findings on the dynamics of the thorax and lung have been translated into three levels of computational models.

The most elaborate is a multidimensional finite element model (FEM) that can resolve the dynamic motion and pressure wave propagation in the parenchyma, taking into account the geometry of the lobes and the nature of the various bounding

surfaces. This model has qualitatively shown the most likely locations of injury: the pleural surface on the blast side. the tips of the lobes, and the regions around the heart and the spinal process.

The second model follows the dynamic motion in a single spatial direction, perpendicular to the lung surface. This model can employ greater spatial resolution at reasonable cost and, therefore, has been used to study the "parenchymal shock" phenomena. This model is also applicable to the Kevlar jacket investigation.

The third model follows the dynamic motion at a single spatial point on the pleural surface. Because of the considerable simplification afforded a single degree of freedom model, it is possible to readily solve the equations and compare the results with a wide range of field data. The model's prediction of pleural injury correlates very well with graded injury from necropsy reports for a wide range of circumstances: single, multiple, and repeated explosions in the free field, as well as a variety of explosions in an enclosure.

Applications. The research into thorax dynamics and lung injury produced several products that were not originally anticipated in the project.

A Compilation of All Field Data on Injury. In the process of testing the validity of the injury prediction model, we found that the existing data had never been assembled and tabulated. Consequently, we compiled all of the available literature, data records, and informal working papers and published these findings in a single source. Electronic forms of the data were also produced that could be manipulated with the analysis software.

The Blast Test Fixture. The modeling work demonstrated the need for better information on blast load distribution on the animal. JAYCOR then conceived a simple test fixture, with multiple pressure probes, that could be used to simulate the geometry of a sheep or a man and collect, in one pass, all of the relevant load data. That device has become a standard field measurement device.

The VU package for field data analysis and reduction. In the process of supporting field studies, it became evident that data analysis was too slow a process to allow the investigator in the field to understand the results of his tests and make modifications. Summer study data was not fully reduced until after the study was completed and the only recourse was to modify plans for the next summer.

JAYCOR analyzed the problem and wrote special data acquisition and analysis software for use in the field. Customized to the acquisition hardware in use by WRAIR, this software, VU, allowed full analysis of all data within minutes of a shot. Problems could be detected and corrected without losing an entire series.

The VU package has been continually expanded and upgraded and is in its sixth major version. It now has full data base features to allow data to be stored, recalled.

compared, integrated, etc. It is one of the principal components of the blast analysis software package.

A simplified model for pleural surface injury was written in a FORTRAN program that allows the user to assess the likelihood of injury from any pressure trace. This program is also part of the blast analysis software package.

Gastrointestinal Tract. Injury to the gastrointestinal tract has received less attention because its consequences tend to be longer term and less life threatening. As a result, little had been done to understand and correlate the occurrence of injury, despite the considerable amount of necropsy data available.

JAYCOR's investigation began by establishing, with direct observation of surrogates and in vitro preparations, the correlation of gas bubble location and injury site. With a firm knowledge of the nature of the injury process, a step-by-step research plan was conceived and executed.

In order to maintain an environment that preserves the critical in vivo characteristics of the GI tract, most importantly the perfusion of blood, yet allows the direct observation and intervention required to quantify the injury process, a special surgical technique was developed. This procedure, designed for rabbit, allows the animal's heart to continually perfuse the intestinal tract while the tract has been removed to a special chamber where blast exposure can be simulated.

Using this perfusion technique, data was collected that defined the typical locations and nature of injury and the local bubble parameters that appear to control the magnitude of injury. Next, materials were tested and selected that gave the same dynamic response as the intestinal sections. Comparisons were made to ensure that the surrogate model in the configuration of intestinal tract also responded as the biological system.

Using the surrogate model, extensive tests were conducted to determine all of the relevant mechanical properties affecting the bubble dynamics. Bubble volume and shape, curvature and strength of the intestinal section, and proximity of sections to neighboring sections and other organs were all assessed with the surrogate model.

From these results, an understanding of the abdominal dynamics in the neighborhood of gas-containing sections emerged. Based on this understanding, a calculational model of the processes was constructed and compared with the surrogate data. With this model, abdominal pressure histories can be translated into local bubble motion and eventually strain rates of the intestinal tissue.

Material properties tests were conducted to determine the elastic properties of various gut sections and to estimate their limiting strengths. This failure limit determines the injury curve, once the relation between the external blast and the abdominal pressure is known.

Working together with WRAIR, field tests were conceived to produce the desired abdominal pressure data. The initial results, from tests piggy-backed onto other studies, were inconclusive because of difficulties in surgically implanting the pressure probes and in knowing the environment at the probe. The signals change dramatically if the probe is in or out of a gas bubble.

To support the field effort, JAYCOR conceived, designed, and tested in the laboratory an apparatus, Probe-in-Balloon (PiB), that can accurately measure the pressure and control the bubble environment. Unfortunately, the field testing was never resumed so that the critical abdominal data was not collected.

Blast Analysis Software Package. The most practical of the products developed under the previous modeling project is a collection of software designed for ready analysis of blast overpressure. The package runs on any desktop computer (IBM PC compatible) and offers a complete environment for performing blast analyses.

The user can reduce data from WRAIR's DASA acquisition system and catalog it in data base files. The user can access any of the previously acquired data in the extensive blast overpressure data base and manipulate (plot, integrate, differentiate, overlay, smooth, clip, etc.) the data or create new databases. Data can be entered from a digitizing pad and placed in the data base. Calculations can be made of the blast overpressure from charges placed in the free field or within enclosures and the resulting pressure traces stored in the data bases. An analysis module allows the user to select any subset of the data and analyze its potential for injury to the upper respiratory tract, the tympanic membrane, or the pleural surface of the lung.

Current Project Results

The work summarized in this report deals with four research areas. The first is the collection, organization, and analysis of animal pathology data which forms the basis for our current understanding of blast related hazard. The second is the refinement and validation of our predictive models of blast injury for the free-field that is the basis for our theoretical understanding of the phenomena and our means to set safety standards. The third is the modeling of combined battlefield trauma which is required to establish combat medicine needs. The fourth is the understanding of blast in complex environments where hazards are increased. Sections 2 through 5 summarize the findings in these areas and guide the reader to other technical documents where the work is described in detail.

2. BLAST PATHOLOGY DATABASE

The first area of research, and the largest effort of the project, was to collect, organize, and analyze animal test data so that model predictions could be validated and refined. It was decided that, in the process, a system, embodied in a computer program, would be developed to properly archive and analyze all future test data. This effort has produced a sophisticated program, PATHOS, which is in active use, and insights into blast injury correlations that could only come from the data of nearly 1000 animal tests.

Database Specification

Working together with Dr. Dodd of the Walter Reed Army Institute of Research (WRAIR) and with experimenters at the Blast Overpressure Test Site, we formulated a specification of the entries to be included in the pathology database. That specification expands upon the entries previously contained in necropsy sheets developed at the Lovelace Institute in Albuquerque, New Mexico. The computer program for entering new pathology data follows this format. The specification is described in Reference 1.

The existing animal pathology data that was collected and analyzed under this contract, however, does not include this level of detail. Consequently, this data must be characterized differently to avoid introducing inordinate speculation. A compromise was arrived at in which a new entry is included for each anatomical location (larynx, trachea, 5 lung lobes, and 13 sections of the gastrointestinal tract) that indicates injury on an ordinal scale. This scheme allows the existing data to be correlated, while not conflicting with more complete data entered later.

Software Development

The pathology database software consists of two parts. The first is a relational database for the entries in the specification sheet and related data on the blast exposure (text data). The second are routines for retrieving and viewing graphical representations of the lung necropsy pictures.

The PATHOS software to enter, modify, and browse the text data associated with the animal pathology has been written in the FORTRAN and C programming languages using the commercially available package of database routines made by INFORMIX. The database now includes all of the blast and pathology entries necessary to store the existing quantitative data and long text fields to store lengthy comments that were part of the Lovelace posting sheets.

The database software to allow the user to enter, modify, and browse through data either in the text form of the old data or in the new, quantitative form. The PATHOS program was reviewed by WRAIR and beta tested at WRAIR for in-house experiments, as well as being sent for outside comments.

As a result of that review of PATHOS, an extensive revision to the pathology scoring sheets was made. Some areas have expanded sufficiently to warrant a new kind of entry screen. We developed a "two-dimensional" entry screen for PATHOS to speed up data entry in certain areas and expanded the data fields to incorporate the revised scoring sheets. The program was re-tested and evaluated by WRAIR several more times until a final product was approved [2].

Compilation of Data

All of the data, magnetic tape, necropsy scoring sheets, strip chart records, field notebook records, photographs, and written reports from previous animal tests that were available to us were compiled and cataloged. There are two areas where data is incomplete: digitized pressure traces from the "double peak" study and the original pathology sheets from one of the Albuquerque tests. The blast data requires the tape recorder used at the Kirtland Test Site, while EG&G has not released the pathology data.

The data comprises test of over 900 animals and the hardcopy form consists of over 7000 pages of text and pictures. A summary of the data is contained in Reference 8.

The pathology data has been organized by test series and by animal within test series. All photographs have been sequentially numbered so they can be cross-referenced within the database. We have made high-quality color reproductions of all of the data. A complete set of the text and pictures, organized by animal in separate file folders has been sent to WRAIR to complete their archival records.

Data Entry

All data on the necropsy posting sheets from earlier tests was entered verbatim into PATHOS. Every animal for which visual pathology data was available was regraded according to the ordinal injury scoring scale. With the assistance of funding from the Defense Nuclear Agency, all gastrointestinal injury was graded and recorded.

All pressure time data available, in all formats, was redigitized and converted to GDIF format for ready plotting with POST and access from INJURY.

The more recent bunker data was available in a format close to the data specification. The data could be entered with less interpretation and with more quantitative value, but all lung data had to be re-scored from photographs to provide sufficient detail. All regrading was checked by WRAIR.

Qualification of the Data

All of the data has been reviewed for consistency and completeness. No obvious inconsistencies have been found, although anomalies have been seen, for example, one animal severely injured when five others with the same exposure are not injured. These differences may reflect animal variability or may later be found to be a reporting error. Resolution of these questions must await the findings of the model tasks.

The overall lung and gastrointestinal injuries have been re-scored for consistency for all of the animals in the database.

The FY90 bunker data from a limited number of tests have been compared with BWAVES calculations. Agreement is satisfactory in most cases where the probe locations are well-defined, but ambiguity exists when the probes are in narrow spaces between the blast test device and the wall.

The data is satisfactorily complete. The earlier tests were less detailed in reporting pathology, but that was expected, since it was not a requirement at the time.

Data Analysis

The database has already answered some immediate needs. At the request of Dr. Dodd we analyzed the existing entries to determine the probable validity of the Bowen correlation in predicting injury. The preliminary results show that injury occurs at blast levels a factor of two or three lower than that indicated by the Bowen curve for threshold lung injury.

An analysis was made of the database to provide a correlation of the incidence of injury for the trachea, lung, and gastrointestinal tract as a function of the blast strength. The Bowen parameter was chosen as the correlate. The statistical fit to the data provides better estimates of the threshold than have been available before and shows that the threshold for injury to any of the organ systems is lower than previously thought.

A report on the findings has been prepared and distributed and is being used by DNA and the U. S. Army Nuclear and Chemical Agency (USANCA) to revise troop safety criteria [13].

Photographic Interpretation

We assembled the hardware and software required to electronically capture the photographic images for the pathology database. Selected photographs showing the lung pathology were scanned into electronic form and used to test software for manipulating the images in analysis. Capability was added to PATHOS to store and display the color pathology photographs.

All of the pictures from the 1990 and 1991 complex wave tests have been scanned and can be called from within the PATHOS database. When the user is in any part of the database, a single keystroke will cause the program to search the photographic data files for the corresponding necropsy pictures and display them in full color and resolution [2].

All of the corresponding GI pathology pictures have been scanned and are part of the picture database. Those pictures can be accessed from within PATHOS in the same way the lung and other organs are [19].

Computer-assisted classification of lung injury has been tested. We are using software that allows the computer to "learn" the visual characteristics of pathology which can be then applied automatically. The results are very encouraging, especially if the original photographs are taken under controlled lighting conditions, and produced automated grading that was judged excellent by trained human standards [4].

All of the 1-pound, room-centered, explosions from the bunker test series were selected to have the lung pathology photographically interpreted. Since each photograph was taken under different lighting conditions, each photograph had to be separately classified. A total of 48 animals (96 images) were classified and analyzed. This set will serve as the basis for a quantitative analysis of the pathology patterns and a comparison with the human-scored pathology results in the PATHOS database.

PATHOS Software Version 1.0

The completed version of the pathology database for free-field exposures and the revised PATHOS software was delivered to WRAIR. A detailed user's manual, including color illustrations of all input screens, was prepared and delivered [5].

The electronic form of the pathology database for all animal tests through the 1990 Bunker Study has been delivered by Dr. Dodd at WRAIR. The pathology database containing all of the free-field data has been printed out in multiple volumes and also sent to Dr. Dodd [18].

3. INJURY MODELING

The biomechanical principles guiding our models of injury prediction (critical stress, irreversible work, material fatigue) had been developed in previous projects and had been shown to provide insight into observed results of isolated tests. With the production of a qualified pathology database containing hundreds of animal tests, it has been possible to assess the validity of the biomechanical models. In addition, we have been able to introduce the concept of population statistics which expands both the precision and utility of the model predictions.

One-Dimensional Model (THOR)

GDIF output was added to the one-dimensional thorax response model, THOR, to facilitate the comparison with experimental data. Eight summer study cases were recalculated using loads from Blast Test Device and the parenchymal pressures compared with measured data. The results are being used in a collaborative paper with WRAIR.

THOR has been used to re-evaluate the relation between pleural pressure and chest wall velocity at high blast loading. As may be recalled, it was learned earlier that the pleural pressure varied linearly with chest wall velocity at low blast loading, and this simplification is the basis of the irreversible work evaluation contained in the INJURY program. Some of the bunker tests (in particular, the exposure of an animal to a 2-pound charge at a range of only 3 feet) produced blast loads in excess of anything previously experienced. Since that case is associated with the greatest injury seen in the bunker series, we want to confirm that the linear relation still holds.

The preliminary results indicate that the pressure-velocity relation is not linear at high loads and, in fact, exhibits a hysteresis behavior. To understand the effect of this finding, we re-ran all of the free-field exposures using THOR (instead of INJURY) and developed a modified work-injury correlation and statistical distribution. We then evaluated a limited number of bunker tests, including the 2-pound, 3-foot case, and found the injury prediction quite satisfactory.

We compared the THOR and INJURY correlations in greater detail to see if there are any significant differences that would warrant our recommending using the THOR model as the standard for injury prediction. We found the INJURY predictions to be satisfactory to predict the overall injury *grade* for the free field and bunker cases considered, but it is likely that a higher dimensional model, such as THOR, will be required to explain the injury *distribution* seen in the bunker shots.

Foam Dynamics Experiments

The foam dynamics tests conducted several years ago confirmed the THOR model findings that the pleural pressure is proportional to the chest wall velocity at low to moderate loads. Recently, some of the bunker studies have resulted in loadings far higher than anything previously studied in the free-field and because these cases led to so much lung damage, it renews an earlier speculation that the pressure-velocity might be nonlinear at high chest wall accelerations.

To investigate this possibility, we re-activated the surrogate thorax test facility. Tests were made at very high accelerations (20,000 to 50,000 g's), measuring both the "chest wall" motion and the "pleural" pressure. The results indicate very erratic behavior during the initial loading, although the linear pressure-velocity relation is re-established later [6].

Multi-Dimensional Free-Field Load Description

Load data taken in the free-field from Blast Test Device and chest wall mounted gages as well as previous EITACC calculational results have been compiled. The results support the following correlation. The blast-side loading is characterized by the reflected wave, while the leeward side is comparable to the incident wave and is delayed in time by about 1 to 2 msec. Further refinement of this description is not justified by the current data. Until a validated computational approach is used, we recommend this simple prescription for free-field loading.

Multi-Dimensional Thorax/Lung Model

Previous Finite Element Modeling (FEM) of the thorax/lung has led to aphysical solutions because of the large material properties difference between the chest wall and the lung parenchyma. A one-dimensional model was developed that represented the chest wall mass as a single node, resolving the previous problems.

The technique of treating the chest wall, and other solid boundaries of the lung, as part of the element nodes has been implemented in a two-dimensional FEM. The resulting solutions are well behaved and agree with the localized one-dimensional results.

We obtained an anatomical model of the human lung to provide specific guidance for refinement of the FEM. Based on that model, a new FEM grid was selected that better resolved the stresses at the pleural surface and whose elements have an initial shape with less distortion. Both of these changes enhance the calculational accuracy.

Refinements have also been made to the chest wall treatment to allow proper description of the rigid nature of the thoracic cage, without compromising the tangential motion of the pleural sac. The thoracic cage now moves as a rigid member, pivoted at the spinal process, while the pleural sac can slide tangentially along the

thoracic wall. As a result, there is no longer an artificial "pinching" of the tip of the lobes between the thorax and the abdominal surfaces.

A series of calculations was made with this refined thorax/lung model. Wave motion was more regular and the thorax showed reasonable displacement patterns. Regions of high stress continue to appear in the tips of the lobes, around the heart and spinal process, as well as at the pleural surface.

Validation of Overall Injury Characterization

We have validated the model against the free field data in the pathology database. The pressure loading was determined in two steps. First, the incidence pressure data was compared with the modified Baker relations to produce consistent peak pressure and duration values. Second, the reflected pressure was determined with the isentropic gas dynamics relations, assuming a constant duration.

The Friedlander waveform for the frontal pressure loading, as determined above, was used in the generalized model for the lung to compute the irreversible work done at the pleural surface of the lung. The linear pleural pressure-chest wall velocity relation was used.

Data on control animals have not been reported for the Albuquerque tests. Consequently, we developed substitute control animal statistics by considering all of the animals exposed to free field explosions that showed no lung pathology. This group was analyzed statistically to determine the mean lung weights and the distribution of lung weights.

The observed lung weights were plotted against the calculated irreversible work. A definite correlation was shown. Furthermore, the scatter of observations around the mean correlation had the same statistical distribution as the control population. This result suggests that the scatter is largely due to animal variability [17].

Little pathology is seen in the left lung, however these null results are confirmed by the model predictions even in cases when there is severe injury to the right lung. The results support the contention that the pleural injury can be determined from the local pressure loading distribution.

INJURY Software

The INJURY software was improved in increments throughout the course of the project in response to changing requirements.

The first step was to modify the program to read the pressure data in GDIF format, the new standard to exchanging data between the software modules. In the process of making this change, it was clear we needed to rearrange the functional aspects of

the program to allow ready access to the model parameters and to provide better output formats for analyzing the data.

The numerical solution algorithm was re-examined. It was discovered that the 5th order Runge-Kutta method, which is ideal for most differential equations, is ill-suited to the sharply peaked pressure traces associated with blast waves. We experimented with an exact analytical solution method, but in the end found that a fully-implicit, time-averaged scheme was not only just as accurate, but was more easily implemented. The code now computes the injury models in a fraction of the previous time (for the same accuracy).

We have provided a link between the pathology and blast databases. The INJURY program requires a pressure-time history to make a calculation of the body dynamics. By linking the databases we are linking the observed injury with the measured pressure record. A single unified database is beyond the scope of the current effort, because major reorganization of the VU file format would be required. Instead, we have created separate GDIF files for each shot that can be used with INJURY. All of the animals in the pathology database, for which a pressure-time trace was available, now have an associated GDIF file for use with INJURY.

In July 1991, version 2.1 of the INJURY analysis software was delivered to WRAIR for review. The new version contains a graphical representation of the statistical distribution of injury for each blast exposure. This feature more correctly represents the distribution of outcomes that does occur.

At the same time, an analysis of the INJURY correlation of the current pathology database was presented. Both lung weight and injury score was compared with the work correlate. The statistical distribution of results around the mean prediction closely matches the statistical distribution in the control population, giving credence to the belief that most of the variation is due to natural population variations.

In September 1991, version 2.2 of INJURY was delivered to WRAIR in which the statistical distribution of URT injury predictions was included. With that version, we included a comparison of prediction with data from the same free-field database. Again, the results support population variability as the primary cause of scatter.

In March 1992, version 2.22 of INJURY was delivered to WRAIR. Several extensions to the generation of pressure waves were added to the program. First, the program can now read any .JIB file generated by software that uses the GDIF language. This feature greatly expands the capability of INJURY. Second, the Friedlander wave option has been generalized to accept any pressure, impulse, duration combination (before the shape factor was fixed at $b = 4$). If the user selects a combination of parameters that will result in an inappropriate shape factor, the program will issue an error message. Third, a Mach Stem option has been added that will generate a Friedlander wave appropriate to the Mach Stem region when the user enters the charge weight and distance. The option uses an empirical correlation to the free-field results for peak pressure and impulse and uses the Baker tables to select the shape

factor, b. The duration is computed from these parameters. Finally, the program will now analyze pressure records in GDIF format of arbitrary length (in the past the signals were limited to 20 ms).

A Record function was added to INJURY to allow the intermediate, transient calculations of the model to be written to a file in GDIF format for later analysis by POST.

More refinements have been added to a version designated INJURY 3.01. First, another pressure wave option allows the user to generate a true free-field Friedlander wave based on the Baker tables from the charge weight and distance. Second, the Mach Stem option was enhanced to check for the sensor being above or below the triple point. Third, the user has the option to define the Friedlander waveforms as either incident or reflected (load) waveforms. Finally, the HALO professional graphics library has been incorporated, which gives the user control over printing (setting printer dots per inch, number of copies, dithering patterns, image size, and ability to print to a file). Black and white as well as color PostScript printers will be supported. Encapsulated PostScript (.EPS) files can be generated which can then be incorporated into many wordprocessor and page layout programs. The new version was delivered to WRAIR in May 1992 and used successfully in the field at the Norwegian tests.

Special programs were written to convert data from other test series into GDIF format for analysis by INJURY. The first converts the data supplied by Aberdeen Proving Grounds for the RAAWS program. The second converts the Norwegian data. which is in an ASYST format.

In support of the RAAWS analysis, a final re-calibration of the injury correlations was made. Ideally, we would calibrate the models using the measured pressure-time histories, however, a complete set of pressure data correlated to the animal pathology data is not available. We do have the physical description of each test (charge type, charge weight, distance, height of burst), so we planned to use INJURY's wave generation options for all cases. Unfortunately, the pressure, duration and impulse data reported in Dr. Dodd's paper on threshold URT injury did not agree with the correlations developed from other free-field tests, so we had to use a modified procedure.

All of the free field data was used in a re-calibration of the lung injury correlation. The incident pressure time-history was generated using the Mach Stem option for all of the cases. The tests were sorted by the work correlate and grouped into nearly equal sized bins. A log-normal (probit) curve was fit to each category of lung injury (none, slight, moderate, severe) for all of the data using a weighted least squares routine. The coefficients of the curves were entered in INJURY and are used to generate the injury severity-frequency bar graph.

The data from Dr. Dodd's paper on nonauditory limits was used to re-calibrate the URT model. First, we tried to use the Mach Stem option, but we found that the

reported pressure values differed significantly from that correlation. Since this data is supposedly the same as that used to generate the correlation, we should have found good agreement. We were unable to locate the source of the discrepancy and because of the urgency of the RAAWS analysis, we chose a different method. The peak pressure and impulse data reported in the paper were taken as correct and the shape factor from Baker's table was selected based on charge weight and distance. The duration (which is often the least reliable blast parameter) was back calculated. These waveforms were used to compute the maximum tracheal stress and the stress correlated with observed injury. The correlation coefficients were entered into INJURY and are used to generate the injury frequency bar graph.

Finally, James' data on tympanic membrane rupture was used to develop a probit fit to the critical stress calculated by the INJURY tympanic model. The new correlation was implemented in INJURY 3.0 and delivered to WRAIR.

INJURY User's Manual

A comprehensive user's manual for INJURY 3.0 was prepared and delivered to WRAIR. The manual uses color images of the screen to describe the program's features [9].

4. COMBINED INJURY EFFECTS

Blast injury and other battlefield trauma place a strain on the military medicine supply system and must be accounted for in determining ranges for engagement with nuclear weapons that will protect friendly troops and civilians. The mathematical modeling approach was applied to this area and produced insights into the long-term casualty generation resulting from a compromised defense system and a mathematical tool for evaluating combined injury effects under battlefield conditions.

Combined Injury Working Group

Meetings were held in various locations over a three-year period to evaluate the effects of combined injury on soldier performance. The meetings were sponsored by the Defense Nuclear Agency and were regularly attended by representatives from the uniformed services and from a wide variety of research institutes. JAYCOR was invited by WRAIR to assist in the formulation of blast injury criteria and later to help integrate the findings mathematically.

Santa Fe, NM	May 23-25, 1989
Bethesda, MD	Sept. 18-19, 1989
Orlando, FL	Jan. 17-18, 1990
Springfield, VA	March 7-9, 1990
Silver Spring, MD	May 28, 1990
Bethesda, MD	Nov. 29-30, 1990
San Diego, CA	Dec. 17, 1990
Alexandria, VA	Jan. 17, 1991
New Orleans, LA	Apr. 21-24, 1992

Each meeting developed the combined injury methodology with expert opinion and discussion of the medical and research experience. As the approach became more defined, JAYCOR took on the role of providing quantitative evaluation of the relation between weapon effects and injury models and of providing a mathematical structure for the overall process. The specific areas became tasks under this contract.

The final meeting of the working group was held in New Orleans on April 21-24, 1992. The group reviewed the performance time-histories gotten from the physician's estimates of symptoms and refinements to the critical dose levels for blast and burn. The recommendations will be considered by USANCA for inclusion in a revision of field manuals and risk criteria. JAYCOR was tasked with providing the computational tools necessary for USANCA to make the final determinations.

Current Injury Models

A complete set of injury models as used in the US Army's Personnel Risk and Combat Casualty (PRCC) handbook was collected. For each physical threat (ionizing radiation, thermal radiation, and blast) the models include a dose-response curve, a dose-incidence curve, and a temporal response curve.

For ionizing radiation, we used the Intermediate Dose Performance (IDP) curves which provide the temporal response of the performance of the average individual for various radiation levels. The dose-incidence curve is taken from the PRCC values.

For thermal radiation, we take the dose-response and the incidence-response relations from the PRCC and the temporal variation from a functional fit to expert opinion data collected by the Combined Injury Working Group.

For blast, we took the dominant effect dose-response relation from the PRCC (in which all effects are lumped together) and the same temporal-response function selected for burns. The dose-incidence curve is taken from the PRCC tables.

These mathematical models formed a base from which combined injury effects could be developed.

MORS Presentation

A presentation was made at the 59th Military Operations Research Society Symposium at West Point in June 1991 on our work "Combined Injury Effects on the Nuclear Battlefield" and it was nominated for a Best Paper award.

The paper deals with the use of mathematical modeling to organize current injury estimates, to formulate quantitatively the military issues, and to combine the physical, biological, operational, and doctrine issues into a single decision making tool.

Model of the Immune Response

A review of the mathematical biology literature has been conducted to assess the state of immune system modeling. That review has produced a large number of references that have been evaluated in terms of the form of the models used and the values of key parameters.

Based on those findings, a comprehensive immune response model was formulated that includes the humoral and cell-based immune response in addition to the previous neutrophil response. A generic (non-immune) damage model was added and multiple symptomatology included. "Performance" can now be expressed as a function of multiple symptoms, in parallel with the IDP formulation.

A parameterization of the results of Loeffler and Wichman's model of stem cell proliferation is used to describe the regeneration following radiation exposure. Data from OKunewick has been used to estimate cell survival rates under exposure to ionizing radiation.

The comparison with data on neutrophil concentrations and the IDP symptomatology results is very encouraging [15].

Mechanistic Model of Combined Injury

Model equations have been formulated to describe the biological effects of ionizing radiation, burns, and mechanical insult. The biological processes considered include the body's repair, infection fighting, and compromise of the immune system. The parameters of the model can be calibrated to reproduce the IDP curves and the burn and blast responses.

The model indicates that under certain combinations of insult, the biological effects are greater than the simple addition of effects. This result is in qualitative agreement with previous animal studies [23].

Computer Program for Combined Effects

A computer program (ComEff) has been written to identify areas of overlapping effects on the battlefield. Nuclear weapon effects (dose) as a function of yield and range have been obtained from USANCA and programmed as a table look-up. The response, incidence, and temporal relations from the survey of current injury model have been programmed. The parameters of these models can be modified and stored as new models. The program determines the regions of the battlefield that will cause prescribed incidences of performance degradation to occur and display these regions as color contours. When the contours are overlaid, the regions of combined effects can be identified.

The ComEff program was upgraded for evaluating injury effects on the nuclear battlefield to allow the description of effect in terms of conditional performance incidence. New analysis screens for evaluating the threat on a location, area, and yield range were added. The code was documented with a user's manual [21].

DNA Technology Transfer Meeting

In September 1990 JAYCOR supported the DNA Human Response Program's First Technical Transfer Conference in Alexandria, Virginia. A summary of the goals and current results of the JAYCOR effort was presented along with a demonstration of the combined effects software.

We presented our work on modeling the threat environment on the nuclear battlefield and the performance consequences at the Second Technology Transfer meeting in December 1991. A poster session was prepared as well as a one-hour presentation. The meeting consisted of presentation sessions and software demonstrations.

The presentation generated a great deal of interest. According to the support staff, the ComEff program was the only software to be requested by every attendee.

Troop Safety Estimates

JAYCOR has taken a major role in the revision of troop safety estimates made by USANCA to include combined injury effects.

We derived a mathematically correct treatment for the inclusion of separate effect incidence data into a combined injury model. This methodology will serve as the basis for the new USANCA calculations. In support of that approach, we have collected the current incidence relations and have evaluated the expert panel findings. We have also developed a computational algorithm for performance decrement due to combined injuries [20].

The expert medical opinion data collected by the Combined Injury Working Group was analyzed for consistency. Problems were identified and a scheme for resolving them was developed.

A mathematical model for incorporating the expert data into the USANCA NWEDS computer program was formulated and presented to USANCA and DNA. The model included the formulation of incidence effects developed earlier.

The mathematical model for incorporating expert opinion data on combined injury effects has been translated into a subroutine in the ADA computer language to be integrated with USANCA's NWEDS program [16].

An enhanced version of ComEff that allows the sensitivity of the range of safety to the model parameters was developed for USANCA so that the expert opinion data could be evaluated [24].

5. COMPLEX WAVE ENVIRONMENTS

The most current and most challenging situation for making reliable blast injury predictions is complex waves, arising from complex weapon or enclosure geometries. Here the prospects for a single, unified treatment to predict all cases would be hopeless without the guidance of modeling. In this project, effort was concentrated on understanding the blast environment itself and, in particular, to determine what level of modeling sophistication will be required to describe conditions of interest.

Compilation of Load Data in Enclosures

A review of the available load data for blasts within enclosures has been performed. The only data sufficiently detailed to serve the purposes of injury modeling is that collected at the BOP Test Site for WRAIR. The Navy charge/volume scaling rules are more applicable to the static overpressure in unvented spaces. The information pertinent to the use of this data for load determination has been entered into the blast database and, where possible, the traces have been digitized for future analysis.

Pressure traces from all of the FY90 Albuquerque bunker tests were received and converted to GDIF format so they can be used in injury predictions and compared with BWAVES calculations.

CFD Calculations

JAYCOR's EITACC computer program has been applied to the simulation of single charge explosions within an enclosure. The results have been compared with the measurements from the Albuquerque Test Site to determine the range of validity of the model and with the method of images computer program BWAVES. The results show that CFD methods can be used to predict much of the detail of the complex waves and to provide an analytical source of data for loading that can be used in injury prediction models. The details of this investigation have been described in a technical report [12].

A paper, "Calculation of Blast in Enclosures," was prepared for the 13th Military Application of Blast Symposium held in Perpignan, France on September 22-27, 1991. The paper dealt with the use of Computational Fluid Dynamics (CFD) to simulate the bunker tests conducted at the BOP Test Site. A particular shot, involving a 2-pound C-4 charge in the center of the bunker and the blast test device near one corner, was analyzed in great detail. An assessment of the physical processes was made and the ability of method of images techniques, such as BWAVES, to capture those processes [13].

The paper was presented at the Symposium by Dr. Stuhmiller. Considerable interest was generated in both the simulation technique and the biological consequences, resulting in discussions with the interested parties and Dr. Dodd of WRAIR and Dr. Stuhmiller.

A paper entitled "A Study of Blast Effects Inside an Enclosure" was prepared for the 62nd Shock and Vibration Symposium and presented in October 1991 by Dr. Philemon Chan [14]. The paper contains a detailed analysis of the shock reflection pattern in an empty bunker based on BWAVES analyses. The higher order reflections are shown to merge into what appears to be a general pressurization. This work complements the previous analysis of loading on the Blast Test Device target.

A series of calculations was made to determine the accuracy of Computational Fluid Dynamics calculations of complex waves for practical application. In particular, the study determined the accuracy of a simulation when no special mesh selection was made. (The previous comparisons had used computational meshes that were specifically chosen for the placement of the charge and the target. To employ such a procedure on a routine basis would make the analysis process quite time consuming.)

Two different meshes with equally spaced cells, 2" × 2" × 2" and 1.5" × 1.5" × 1.5" on a side, were used to model a 1/8th section of the bunker. The total number of cells used was 17,280 and 40,960, respectively. The results showed that almost all of the significant features of the pressure time history could be captured by the coarser grid. The only feature not captured is the peak pressure caused by the initial wave reflection. Using a much finer grid in this spatial location is required, but such a grid would increase the overall run time by a large factor without adding any other accuracy. Several methods for empirically correcting the peak value were explored, but none were satisfactory. Since the impulse is reasonably predicted (at time intervals of a small fraction of a millisecond, only the impulse interacts with the chest wall dynamics), we believe that the injury prediction results will not be affected.

The "standardized" computational setup, using 2" × 2" × 2" cells, was used to analyze the bunker tests using one pound charges. Each case was compared with EITACC calculations and with other test results. The comparisons were used to determine how well the CFD model captured the test data and to assess how different the blast environments are in these tests.

Recommendations for Bunker Studies

As part of our planned contribution to the blast program, we investigated room geometries that would produce complex wave fields that are critical to the understanding of this environment. The matter was discussed with Dr. Dodd from WRAIR and Mr. Yelverton from EG&G at the MABS 13 meeting. We determined that the constraints on design should include working within the current bunker geometry and adding internal blockages that were reasonable to fabricate. It was decided that

a floor-to-ceiling partition, thick enough to be built from I-beams would be satisfactory.

We proceeded to make EITACC calculations with various width partitions, investigating which sizes would produce the most interesting effects. The results of that investigation were presented to WRAIR at a project review meeting at the end of October.

The results confirmed that even a single, internal partition greatly modified the blast field, producing new locations of high pressure concentration. To visualize the results, the pressure fields were plotted on our workstation, using a user-controlled interaction that allowed the point of view to be changed contiguously. The results were described in some detail in the presentation material, but a particularly striking result was that the section of the partition on the side away from the detonation could produce the regions of largest peak overpressure, despite their apparent "shielding." Based on these calculations, recommendations were made for future test configurations and instrumentation placement.

Extension of the BWAVES Model

We have analyzed the predictions of the BWAVES code. Several areas of improvement have been identified. First, the current algorithm for determining the intersection of a blast ray with a reflecting surface was found to be sensitive to numerical precision. A new algorithm has been derived and tested. Second, the previous algorithm terminated the image-generating cycle after a fixed number of reflections. Further analysis revealed that many higher-order reflections are important to the pressure signal in the 10 to 20 msec time frame. It appears that part of the discrepancy with data, that had earlier been attributed to pressurization effects, are actually explained by multiple reflections.

The BWAVES code has been significantly improved. The geometry of the wall has been generalized to allow for a plane surface bounded by a polygon with an arbitrary number of edges. The previous algorithm required a wall to have four sides. Furthermore, the new algorithm allows a wall to have arbitrary orientation. The previous algorithm required a wall to be parallel to the coordinate lines. Consequently, the geometry of a vehicle, such as the Armored Personnel Carrier, which has a slanted back roof and which cuts the side walls into five-sided figures, can be described.

The algorithm has been further improved in the selection of images. The previous method retained all possible images. The number of such images grows exponentially fast as the order increases that many higher-order images were not computed. On the other hand, many of the higher-order images are not physically realizable. The old method did not discover the spurious images until the time of pressure reconstruction. The new algorithm is able to eliminate spurious images as they are generated. As a result, calculations can now be made routinely to 7th order in the same storage as was required for 3rd order before.

Finally, an ambiguity having to do with corner reflections has been resolved. Under certain ideal locations of charge and sensor, the ray passing from image to the sensor can intersect the exact corner between two walls, resulting in an ambiguity in the calculation. The problem has been restated to assign the corner to a single wall in a mathematically consistent manner.

A technical report on the BWAVES code has being written [11].

Validation Against CFD Model

We have compared the BWAVES calculations with the EITACC CFD calculations. The agreement is qualitatively good, but there are clearly features that only the CFD calculations can capture. The investigation will focus on the physical origin of those differences and whether they can be incorporated into the BWAVES code.

BWAVES Upgrade

The new algorithm described in reference 11 was coded into BWAVES and tested. The program was given a user controlled interface for setting up the geometry of the enclosure and the placement of the charge and sensor. The calculated pressure time-history can be viewed from within the program and a GDIF-compatible file is written for use with other software elements. The code has been delivered to WRAIR.

Validation of the BWAVES Injury Model

WRAIR proposed that the model be given a blind test against the FY90 bunker data. We used BWAVES to generate load distributions on the front and back sides of the animal. We chose not to use the measured blast test device data because we could not resolve apparent inconsistencies in the data in the time allowed for the prediction. The BWAVES loadings, however, agreed fairly well with the measured traces.

The predicted loads were used in the generalized model to obtain values for the irreversible work for each of the 70 tests. A spreadsheet was prepared with the work values and test conditions.

A meeting was held at WRAIR in which WRAIR staff entered the observed lung weights into the spreadsheet and a plot of predicted and measured values was made. The results were quite good. The observed data fell within the statistical distribution band for almost every case and the agreement for the complex waves was as good as for the free field cases.

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